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Effects of Air Pollution on Human Exercise Performance

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Introduction and Historical Perspective

Most of us would like to live, work and exercise in a pristine environment. Sports such as cross country running, skiing, orienteering and kayaking seem to be associated with unpolluted environmental conditions. Unfortunately, the realities of modern life are very often different from this ideal. Most Americans live in or near a metropolitan area. These cities, with their attendant industry, automotive traffic and higher population densities, are large-scale pollution sources. It is evident that living in a city can routinely bring us into contact with considerable amounts of air pollution.

Air pollution is not strictly an urban problem. The smog generated by agricultural burning and mining operations can generate staggering amounts of pollution. Natural disasters such as forest fires, dust storms and volcanic eruptions often result in large amounts of airborne contaminants.

In recent history there has been a succession of air pollution catastrophies. ~~A good~~ example of this is the 1952 London episode. At that time in London, coal and coke burning provided the energy for industry and home heating. England's consumption of these fuels resulted in 4.7 million tons of the pollutant sulfur dioxide (SO_2) being discharged into the air over southern England each year (18). In the first week of December, 1952, the weather conditions in London left a thick fog trapped beneath a thermal inversion layer. The air was stagnant and the smoke, soot and sulfur dioxide from the burning coal and coke built up in the atmosphere. Visibility was so drastically impaired that the public buses were forced to drive with their lights on during the day. The level of SO_2 in the air averaged .7 ppm, which is five times the United States' primary national average air quality standard. The concentration of SO_2 topped out at 1.3 ppm.

Twelve hours after the fog set in and the smog began concentrating, the hospitals in London began admitting extraordinarily large numbers of patients for respiratory problems. The symptoms were a dry cough, sore throat, nasal discharge and sudden bouts of vomiting. Those individuals with a previous history of respiratory trouble were the most seriously affected.

Figure 1 shows the relationship between the increase in atmospheric SO_2 and the death rate. The British Committee on Air Pollution estimates that 4,000 extra deaths over the normal number occurred from December 2 to December 9, 1952. Unfortunately, this episode was not an isolated case. In the winter of 1956 another smog bank covered London, resulting in more than 1,000 excess deaths due to exposure of sulfur dioxide and particulates.

The response to these large air pollution catastrophies has been the development of standards for allowable levels of atmospheric pollutants. In the United States, a number of different regional and national standards have been developed. Among these are the Pollutants Standards Index and the National Average Air Quality Standards.

Environmental Conditions Leading to Smog Build-up

Two essential factors are needed for a smog problem to develop: a source of pollution and an environmental trap. The pollution source can be exhaust from a vehicle, an industrial source such as a smelter, or the dust ejected by a volcanic eruption. In general, persistent, chronic sources are more significant in their effects. Nonetheless, it is hard to ignore the impact of a forest fire or Mt. St. Helens erupting.

An example of a terrain trap is the area around Denver, Colorado. **Figure 2** shows that Denver sits at the bottom of a large basin, forming an ideal collecting trap for the industrial and automotive pollutants in that area.

Thermal inversion conditions often provide a ceiling that bars the escape of polluted air from a valley or basin. In normal atmospheric conditions **(Figure 3a)**, the air over the earth gets colder with increasing altitude. Under these conditions, the pollutants, which are relatively warm, rise through the layers of dense, cold air. Inversion conditions **(Figure 3b)** occur when a layer of warm air is interposed between layers of colder air. These warm layers can be very stable and sometimes can persist for days. The inversion layer forms a roof that traps the upward movement of airborne pollutants, and it then spreads horizontally beneath this inversion. These elements of a pollution source and an environmental trap are common to almost all situations where there is a build-up of atmospheric pollution.

Pollutants and Their Effects on Performance

Pollutants can be divided into primary and secondary pollutants. Primary pollutants are those that exert their effects as they come directly from the source. Secondary pollutants are formed by the interaction of primary pollutants with each other, with other compounds or with ulraviolet light. The primary pollutants are: carbon monoxide, sulfur oxides, nitrogen oxides and primary particulates.

From the standpoint of coaches and athletes, carbon monoxide is the most important of the primary pollutants. The principle source of carbon monoxide is automotive exhaust. Carbon monoxide exerts its effect by binding to and blocking the oxygen-binding sites on hemoglobin in the red blood cells. Hemoglobin has an affinity for carbon monoxide that is 230 times greater than its affinity for oxygen. This high affinity means that once the carbon monoxide is bound to hemoglobin—in turn, forming car-

Figure 1. The number of excess deaths closely followed the changes in SO_2 during December, 1952, in London, England. After McCafferty, (13).

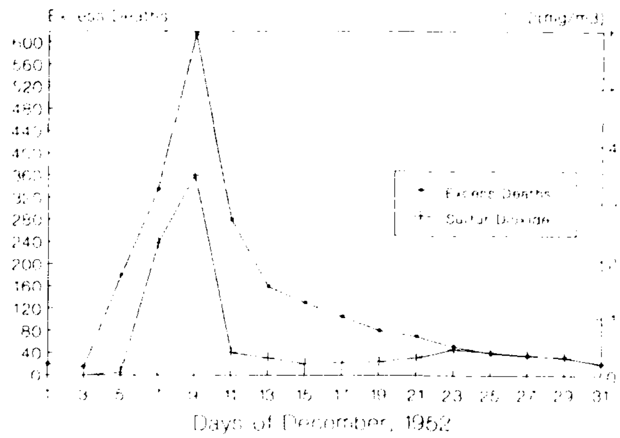


Figure 2. Denver sits in the bottom of bowl-like basin that forms an ideal trap to contain the air pollution generated in this area. Reprinted by permission (8).

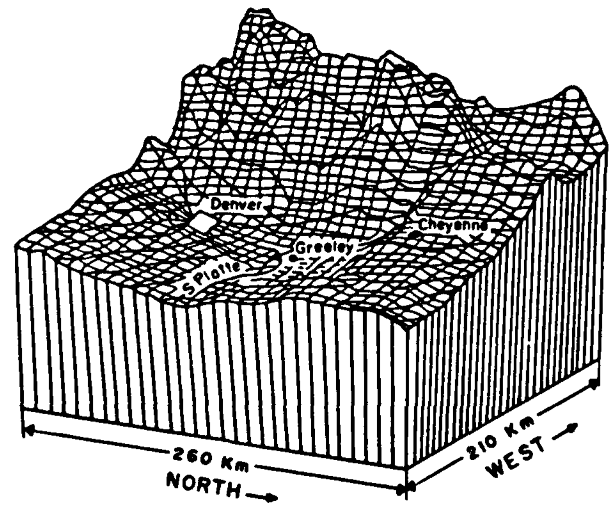
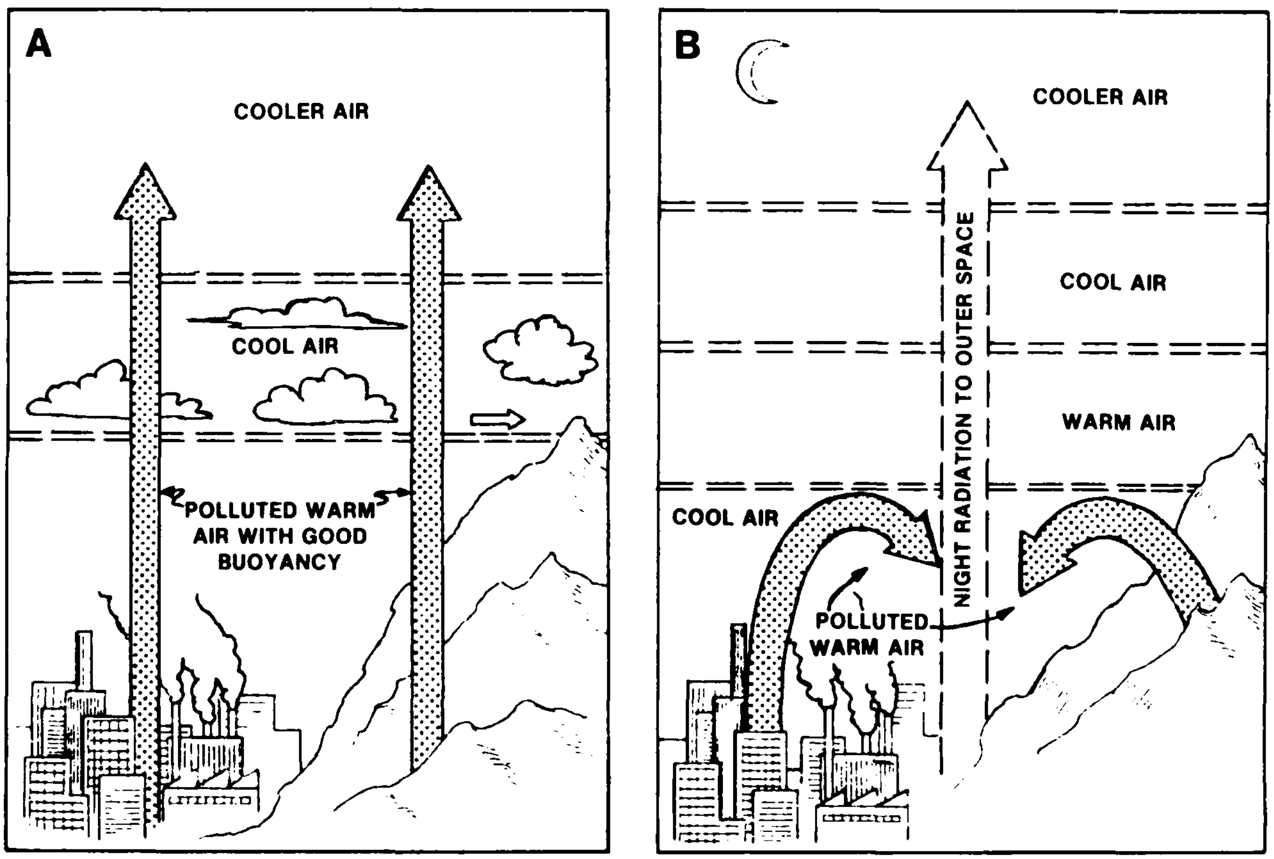


Figure 3. Panel A shows normal atmospheric conditions in which the air temperature decreases with elevation gain. Panel B shows a thermal inversion in which a layer of warm air has been trapped between layers of colder air, blocking the upward flow of warmer, polluted air. After Shaheen, (18).



boxyhemoglobin (COHb)—it is very difficult to detach it from the hemoglobin molecule (7). By preventing oxygen from attaching to the binding sites on hemoglobin, the ability of blood to carry oxygen is reduced.

Another effect of carbon monoxide binding to hemoglobin is that it causes the remaining binding sites on that particular hemoglobin molecule to develop a higher affinity for oxygen. This makes it more difficult for the hemoglobin to release its oxygen to the tissues that need it. **Figure 4** demonstrates the results of increased COHb concentrations in the blood. The vertical axis shows the percent saturation of the blood by oxygen. The horizontal axis shows the partial pressure of oxygen in the blood. In blood with increased levels of COHb, the oxygen dissociation curve is shifted to the left. This is an indication of the hemoglobin's elevated affinity for oxygen, which makes tissue oxygen extraction more difficult. This means that increased levels of carbon monoxide in the blood compromise both the transport of oxygen in the blood, and the extraction of oxygen to the tissues.

The immediate impact of this on exercise performance is that as the concentration of COHb in the blood increases, there is a decrement in maximum oxygen consumption (**Figure 5**). In 1975 Horvath et al. (9) noted a concentration threshold at 4.3 percent, below which there were no decrements in maximum oxygen consumption.

Other effects of increased levels of carboxyhemoglobin are: decreases in peak $\dot{V}_E$ during maximal exercise (20), decreases in maximal exercise time (4, 15), decreases in exercise time before the onset of angina (2) and an increase in submaximal heart rate (5, 20).

Another of the primary pollutants are the sulfur oxides. These compounds are the result of incomplete combustion of fossil fuels. Approximately 98 percent of all atmospheric sulfur initially is sulfur dioxide (13). Sulfur dioxide transiently increases the resistance to flow in the upper respiratory tract. This effect is most prevalent in asthmatics, but doesn't significantly decrease submaximal exercise performance in normally healthy individuals. There have been no studies at this time that have examined the effects of SO_2 on maximal exercise (14).

Of the pollutants in the nitrogen oxide family, nitrogen dioxide is known to be potentially harmful to humans and is the only one that has been extensively studied. The sources of nitrogen dioxide are high temperature combustion processes, with motor vehicle exhaust accounting for about 40 percent of the total emissions (13). There have been limited studies concerning nitrogen dioxide's effects on submaximal performance, and there have been no studies addressing the effects of NO_2 on maximal exercise. The studies of submaximal exercise have shown nitrogen dioxide to be a mild upper respiratory tract irritant, but no significant effects on pulmonary function have been found (14).

The inhaling of particulates from soot, cigarette smoke or dust can serve as respiratory tract irritants causing bronchoconstriction (19). The effects of these irritants on exercise have not been studied to any extent in humans. Particles of different sizes exert their impact at different locations in the respiratory tract. The larger particles are filtered out by the nose and mucous of the upper respiratory tract. The smallest particles find their way down to the alveoli, where their action occurs. The body defends itself against particulate pollutants by changing the depth and pattern of breathing, and by increased mucociliary transport (9, 19).

Secondary pollutants are important because they evolve from the interaction of other pollutants, water, salts and ultraviolet light. The secondary pollutants include ozone, peroxyacetyl nitrate and various aerosols. The most important of these is ozone. Ozone is formed by the interaction of oxygen, nitrogen dioxide,

Figure 4. Increases in inspired CO (from 0% to 20% to 40%) cause a leftward shift in the oxygen dissociation curve. Reprinted by permission (3).

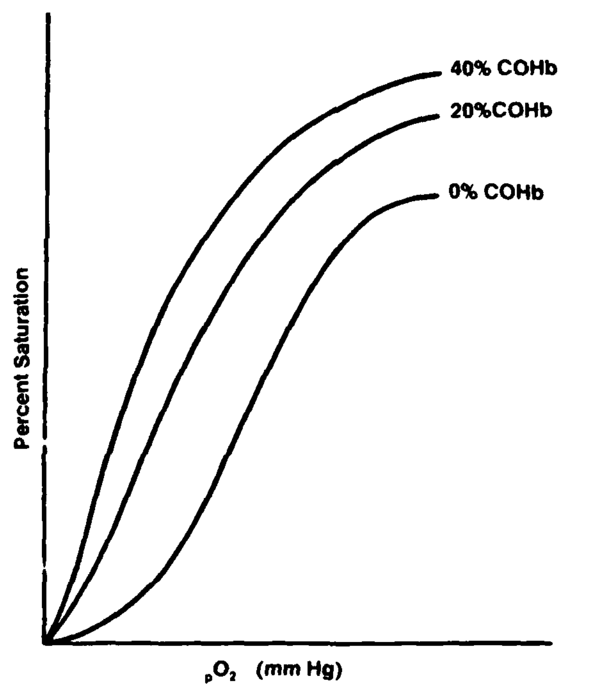
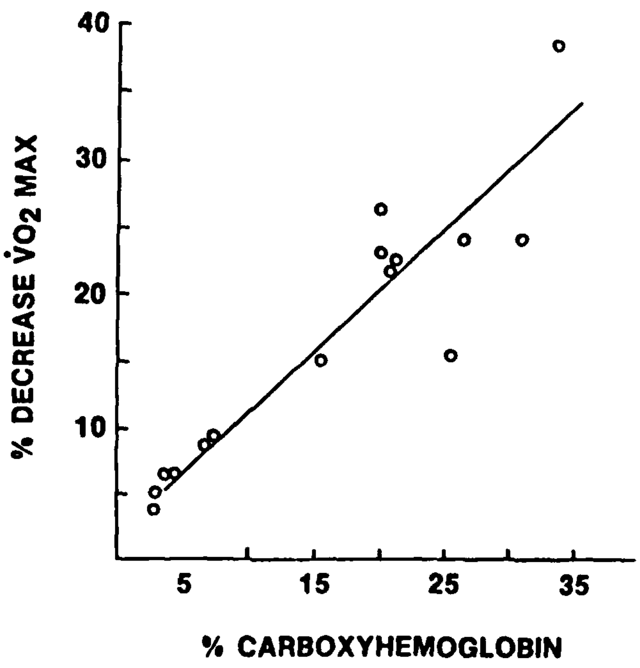


Figure 5. As HbCO increases, a decrement in maximum aerobic power occurs. After Horvath, (9).



hydrocarbons and ultraviolet light. The production of ozone is closely tied to sunlight and, consequently, is highest just after midday (13).

Ozone is a potent airway irritant that can cause reflex bronchoconstriction at high concentrations. Studies of submaximal exercise with exposure to ozone show that the problems encountered are more associated with discomfort in breathing than in the physiological impairment of the exercise process. It appears that there is no decrement in submaximal exercise performance associated with ozone exposure (14).

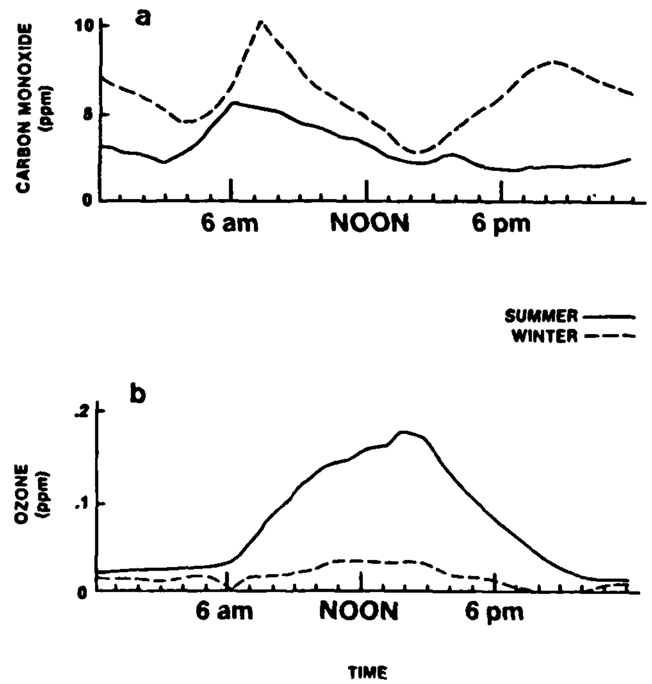
With respect to the effects of ozone on maximal exercise, very few studies have been completed. Savin and Adams (17) found no change in exercise capacity or cycling $\dot{V}O_2$ max, associated with ozone concentrations. Horvath et al. (10) exposed subjects to different concentrations of ozone. They found no significant changes in treadmill $\dot{V}O_2$ max, HR max or maximum performance time associated with different ozone concentrations. The evidence regarding ozone is so limited that it is difficult to draw conclusions.

The primary source of atmospheric peroxyacetyl nitrate is automobile exhaust. This compound is a potent eye and nose irritant and is often responsible for the burning eye sensation that accompanies exposure to smog. Again, there are limited studies available concerning either submaximal or maximal exercise. The studies that have been completed cite blurred vision, eye irritation and eye fatigue as prominent symptoms of exposure (6). None of the studies has demonstrated clear evidence of respiratory, metabolic, or thermoregulatory distress with peroxyacetyl nitrate exposure during submaximal exercise (14). Studies by Raven et al. (15, 16), found no decrement in $\dot{V}O_2$ max during peroxyacetyl nitrate exposure of various concentrations. These authors speculate that the maximum concentration of peroxyacetyl nitrate used may have been below the threshold at which physiologically meaningful changes may have occurred.

Aerosols are formed by the interaction of various acids and salts. The most commonly studied aerosols are ammonium sulfate, ammonium bisulfate and ammonium nitrate. These compounds are eye and upper respiratory tract irritants. While they may cause discomfort during either submaximal or maximal exercise, they do not appear to be conclusively linked to exercise performance decrements (9).

In summary, only carbon monoxide shows a clear decremental effect on maximal exercise performance. Other compounds (i.e. ozone, SO_2, NO_2 and peroxyacetyl nitrate) cause irritation of the eyes and respiratory tract, but there is little or no evidence that they cause decrements in either maximal or submaximal exercise performance. There has been a genuine lack of studies dealing with pollutant effects on exercise capacity and performance, especially those that have adequate sample sizes to detect small changes in performance. While it is not clear that some pollutants have significant effects on performance, it makes sense to treat these compounds as potential problems rather than ignore them until it is too late.

Figure 6. Seasonal and daily fluctuations in CO and ozone concentrations in the Los Angeles area. Reprinted by permission (13).



Training in Smoggy Conditions

The key issues to consider in order to minimize the impact of smog on exercise training can be summed up in four words: timing, location, intensity and duration.

Timing

It is important to consider the timing of workouts relative to smog build-up. Some pollutants, like carbon monoxide (**Figure 6a**), show rapid increases in concentration following times of peak automotive traffic. Although there is some seasonal change in the overall levels of carbon monoxide, the main changes occur during the course of each day (13).

Other pollutants (i.e. ozone), depend on heat and ultraviolet radiation from the sun for their formation. **Figure 6b** demonstrates a strong build-up of ozone in the early afternoon. The seasonal occurrence of ozone is well known, and summer ozone problems are clearly linked to increases in the duration and intensity of solar radiation. In general, the best times of day to avoid smog are early morning or late afternoon (13).

Location

This may seem obvious, but athletes should make a conscious effort to avoid exercising near a pollution source. To avoid the exhaust of passing vehicles, run on the upwind side of the road. If forced to stop at an intersection, stay away from the exhaust pipes of the stopped vehicles. If necessary, stand well away from the intersection to avoid the higher concentration of pollutants that occur in that area. Don't be obsessed by trying to avoid every last bit of pollution, just use your common sense. Also, be aware that air pollution can occur in indoor settings as well. A classic example of this is a case in which a group of young ice hockey players suffered CO intoxication at an indoor rink. The source of the CO was a gasoline powered ice resurfacing machine (1).

Intensity and Duration

The concept of effective dose is important to understanding the effect of intensity on exercise performance in smog. The effective dose is the product of the concentration of the pollutant, the volume of air breathed per minute (which is a reflection of exercise

intensity) and the duration of the exercise (12). While all three of these factors affect the pollutant dose during a workout, only the duration and intensity (ventilation volume) can be controlled by the athlete.

[Pollutant Conc.] X (Ventilation) X (Duration) = Effective Dose

(A) [1] X (6 liters) X (480 min) = 2880

(B) [1] X (120 liters) X (30 min) = 3600

Equation (A) demonstrates the pollutant dose for a sedentary person having an eight-hour exposure to a pollutant of a concentration of one, and with a minute ventilation of six liters. This gives an effective pollutant dose of 2,880 units. Equation (B) shows the results of this person exercising for only 30 minutes in the same concentration of pollutants. At a ventilation level of 120 liters per minute, he or she would receive an effective dose of 3,600 units, or 125 percent of the sedentary eight-hour dose in just 30 minutes. It is easy to see how exercise intensity affects the magnitude of a pollutant dose.

Athletes can effectively alter the "intensity" of their workouts by reducing their running speed or by dropping the number of repetitions and sets in their weight workouts. Use the smoggy days for technique workouts, rather than the intensive body building workouts that would demand high ventilation rates. Weight workouts with high loads (1 RM), low repetitions and long rest periods between sets also would be appropriate for smoggy day training.

It also is important to limit the duration of exposure to the polluted air. By cutting back on the overall length of exposure and limiting the intensity of the exercise, the effective dose of pollutants can be minimized.

Competing in Smoggy Conditions

Important international, intercollegiate or interscholastic, competitions typically are held in or near large cities. Five of the last seven summer Olympic Games were held in cities with histories of high levels of air pollution. Unfortunately, athletes cannot control the atmospheric conditions in which they compete. They are stuck with the conditions at hand.

For some sports, the physiological decrements caused by smog exposure may not be substantial. But, for those sports with high metabolic demands, the impact of air pollution can be significant. At the highest levels of competition, the difference between victory and defeat often is a tiny fraction of the overall performance. These differences of performance are much smaller than those discernible in most of the air pollution studies conducted to date. Unfortunately, the sample sizes needed to detect such small changes in performance are far larger than those found in current studies. Studies of a more epidemiological nature are needed to more fully assess the impact of smog on exercise performance—particularly high-level athletic performance.

What then, are the strategies to help an athlete deal with competing in smog? First, minimize exposure to pollutants en route to the competition. This seems obvious, but we all have been caught in a traffic jam with the windows of the car open. Another thing to avoid is riding with someone smoking cigars or cigarettes in the car. Secondary cigarette smoke is loaded with carbon monoxide, nicotine and particulates, all of which have detrimental effects on health and performance (13).

Secondly, arrive at the site of the event early. This is most important in sports with high metabolic demands. This is to allow the maximum time to rid oneself of carbon monoxide picked up while traveling. The time needed to wash 50 percent of the CO from the blood ranges from three to four hours (13).

When you get to the competition site, minimize physical activity. By keeping activity low, an athlete may cut his or her dose of pollutants prior to the event. The intensity of warm-ups should be as low as possible.

Last but not least, avoid pollution sources while competing. Stay away from vehicles on road race courses. Running on the upwind side of a busy road can be a useful strategy for coping with automotive pollutants.

Summary

First, heed the weather and terrain conditions in the areas where you or people in your charge will be exercising. Evidence shows definite performance decrements only from carbon monoxide. It is quite possible that the studies of other pollutants (i.e. NO_3, SO_2, ozone, peroxyacetyl nitrate, etc.), were not able to detect the small performance decrements that may have been caused by those agents.

Guidelines for Training in Polluted Conditions

(1) Minimize the impact of air pollution on training by cutting the intensity and duration of workouts. This can be done by:

Reducing the exercise rate (running, cycling or rowing cadence).

Dropping the number of reps and sets in weight workouts.

(2) Use these times for technique-oriented workouts.

(3) Avoid weight workouts (high repetition, moderate weight, low interset rest) or other workouts (intervals, race pace or overpace work) that would demand high ventilation rates.

Strategies for Competing in Polluted Conditions

(1) Avoid exposure to pollutants while traveling to the event site.

(2). Arrive at the site early to allow the athlete's body to rid itself of as much CO as possible.

(3) Minimize pre-event exercise (including warm-up activity) to limit exposure to polluted air.

(4) Avoid pollution sources during the event.

References

1. American Medical Association. (1984) Carbon monoxide intoxication associated with use of a resurfacing machine at an ice-skating rink. **JAMA.** 251:1016.
2. Anderson, E.W., Andelman, R.J., Strauch, J.M., Fortuin, N.J. and J.H. Knelson. (1973) Effect of a low-level carbon monoxide exposure on onset and duration of angina pectoris: a study in ten patients with ischemic heart disease. **Ann. Intern. Med.** 79:46-50.

3. Chiodi, H., Dill, D., Consolazio, F. and S. Horvath. (1941) Respiratory and circulatory responses to acute carbon monoxide poisoning. **Am. J. Physiol.** 134:683-693.
4. Drinkwater, B.L., Raven, P.B., Horvath, S.M., Gliner, J.A., Ruhling, R.O., Bolduan, N.W. and S. Taguchi. (1974) Air pollution, exercise and heat stress. **Arch. Environ. Health.** 28:177-181.
5. Ekbolm, B. and R. Huot (1972) Response to submaximal and maximal exercise at different levels of carboxyhemoglobin. **Acta. Physiol. Scand.** 86:474-482.
6. Gliner, J.A., Horvath, S.M., Drinkwater, B.L. and J.C. Sutton. (1975) Man's physiologic response to thermal and pollutant stress. **J. Appl. Physiol.** 39:628-632.
7. Guyton, A.C. (1986) **Textbook of Medical Physiology.** Seventh edition, Philadelphia: W.B. Saunders.
8. Haagenson, D. (1979) Meteorological and climatic factors affecting Denver air quality. **Atmospheric Environment.** 13:79-85.
9. Horvath, S.M.(1981) The impact of air quality in exercise performance. **Exercise and Sports Sciences Reviews.** D.I. Miller (Ed.). Philadelphia: The Franklin Institute Press. pp. 265-296.
10. Horvath, S.M., Gliner, J.A. and J.A. Matsen-Twisdale. (1979) Pulmonary function and maximum exercise responses following acute ozone exposure. **Aviat. Space Environ. Med.** 50:901-905.
11. Horvath, S.M., Raven, P.B., Dahms, T.E. and D.J. Gray. (1975) Maximal aerobic capacity at different levels of carboxyhemoglobin. **J. Appl. Physiol.** 38:300-303.
12. Larson, D.C. (1985) Toxic vapor exposure and aerobic exercise. **Physician Sports Med.** 13:76-83.
13. McCafferty, W.B. (1981) **Air Pollution and Athletic Performance.** Springfield, Ill: Charles C. Thomas Publishers.
14. Pandolf, K. (In Press) Air quality and human performance. **Human Performance Physiology and Evironmental Medicine at Terrestrial Extremes.** Pandolf, K., Sawka, M. and R. Gonzalez (Eds). Indianpolis, Ind: Benchmark Press Inc. Ch. 16.
15. Raven, P.B., Drinkwater, B.L., Horvath, S.M., Ruhling, R.O., Gliner, J.A., Sutton, J.C. and N.W. Bolduan. (1974) Age, smoking habits, heat stress, and their interactive effects with carbon monoxide and peroxyacetyl nitrate on man's aerobic power. **Int. J. Biometeor.** 18:222-232.
16. Raven, P.B., Drinkwater, B.L., Ruhling, R.O., Bolduan, N.W., Taguchi, S., Gliner, J.A. and S.M.Horvath. (1974) Effect of carbon monoxide and peroxyacetyl nitrate on man's maximal aerobic capacity. **J. Appl. Physiol.** 36:288-293.
17. Savin, W.M. and W. C. Adams (1979) Effects of ozone inhalation on work performance and VO_2 max. **J. Appl. Physiol.** 46:309-314.
18. Shaheen, E. (1974) Environmental pollution: Awareness and Control. **Engineering Technology Incorporated.** Mahomet, Ill. pp. 27-44.
19. Widdicombe, J.G., Kent, D.C and J.A. Nadel. (1962) Mechanism of bronchoconstriction during inhalation of dust. **J. Appl. Physiol.** 17:613-616.
20. Vogel, J.A. and M.A. Gleser. (1972) Effect of carbon monoxide on oxygen transport during exercise. **J. Appl. Physiol.** 32:234-239.